GALACTIC CALIBRATION OF THE CEPHEID PERIOD-LUMINOSITY RELATION:

I. DISTANCE AND REDDENING TO THE CLASSICAL CEPHEID DL CAS IN THE OPEN CLUSTER NGC 129

ROBERT J. 1111,1, and WENDY L. FREEDMAN

The Observatories

Carnegie Institution of Washington

813 Santa Barbara St.

Pasadena, CA 91101

1IARR% l?. MADORE

NASA/IPAC Extragalactic Database

Infrared Processing and Analysis Center

California Institute of Technology

Jet l'repulsion Laboratory, MS 100-22

Pasadena, CA 91125

REBECCA A. BERNSTEIN

Robinson lab, MS 105-24

Division of Physics, Mathematics and Astronomy

California Institute of Technology

Pasadena, CA 91125

Received..

Address for Proofs:

Robert Hill

The Observatories of the Carnegie institution of Washington

813 Santa Barbara St.

Pasadena, California 91101

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ABSTRACT

Based on newly acquired UBVRI CCD photometry, wc present a deep color-magnitude diagram for the Galactic open cluster NGC 129, which contains the 8.00 clay period Cepheid DL Cas, The stellar photometry is first used to derive the mean color excess for the cluster; wc find $E(B-V) = 0.57+0.01$ msg. However, the cluster shows evidence for differential reddening, and wc therefore explore, in depth, the problems associated with dereddening these stars individually using the color-color diagrams. From main-sequence fitting wc derive a distance modulus of $V_o - M_V = 11.103{:}0.04$, corresponding to a distance of 1660+ 30pc. 'l'his distance implies an absolute magnitude of $M_v = -4.00 \pm 0.17$ mag for 1)1, Cas. The larger error associated" with the absolute magnitude for the Cepheid is duc to the uncertainty in determining the color excess of DL Cas itself. Wc discuss potential sources of systematic error in the calculation of the distance modulus and find that errors in the reddening law and the Zero Age Main Sequence could still result in systmatic errors as large as ± 0.27 msg.

Keywords: clusters: open - stars: Cepheids

1. INTRODUCTION

Many important problems in astronomy and cosmology require an accurate knowledge of the distances to extragalactic objects. Onc of the most important distance indicators used in establishing the extragalactic distance scale is the Cepheid period-]uminosity (1'1.) relation. Cepheids provide a means of making the critical step of tying together distances to objects within our Galaxy to galaxies within and beyond the Local Group. The imminent extension of the Cepheid distance scale to the Virgo cluster using the *Hubble Space Telescope* (Freedman ct al. 1994) will allow a much more accurate calibration of the methods (eg. Tully-Fisher and surface brightness fluctuations) which can be used to measure distances on scales which should yield an accurate determination of the Hubble constant, It is therefore of great importance to have an accurate calibration of the PL relation.

The Cepheid 1'1, relation, as it is applied, is a linear relationship between the logarithm of the pulsation period of a Cepheid and its mean absolute magnitude. The calibration of this relationship thus requires a determination of its slope and zero-point. The slope is generally best determined by observations of Cepheids in the Large Magellanic Cloud, since it contains a large number of Cepheids which can all be treated as being at the same distance (Madore & Freedman 1991).

The zero-point of the PL relation is found by independently determining the distances to a sample of Cepheids. After Cepheids were first discovered in Galactic clusters (Irwin 1955), it was realized that a suitable sample might be comprised of Cepheids in open clusters, for which distances could be determined by main-sequence fitting. Despite significant efforts, the number of Cepheids found in clusters is relatively small; the recent review by Walker (1988) lists only 18 Cepheids. Furthermore, many of these clusters arc not well studied, and new observations made with modern detectors and techniques can provide much more data than is presently available for these objects. Although Walker (1985a,b, 1987a,b) has published deep CCD observations of several of the southern Cepheid clusters, most of the northern clusters arc lacking similar data, Our goal in this series of papers is to provide a database of deep CCD observations of Cepheid clusters accessible from the northern hemisphere. The clusters and associated Cepheids arc listed in '1'able 1. We will develop objective methods for dealing with the variable, and often large, amounts of interstellar reddening towards these clusters and apply these methods in a uniform way. The dereddened data will then be used to estimate the distances to these clusters, and thereby the associated Cepheids, by main-sequence fitting. Finally, the results will be used to redetermine the zero-point of the Cepheid 1’1, relation.

NGC 129 is an open cluster which contains the classical Cepheid DL Cassiopeia. The membership of DL Cas in NGC 129 has been verified by both its proper motion (Lenham & Franz 1961; Lavdovski 1961; Frolov 1975) and radial velocity (Kraft 1958; Mermilliod, Mayor, & Burki 1987; Harris et al. 1987). Although the distance to NGC 129 has been estimated in several previous studies (eg. Arp et al. 1959; Schmidt 1980; Turner et al. 1992), accurate photometry has been obtained for only a small sample of the brightest stars. We present here new UBVRI, CCD data of 1270 stars in the direction of NGC 129 (see §2). After comparing our data to previously published photometry (§3), we derive the reddening and distance to the cluster using the technique of main-sequence fitting (§4 and §5).

11. OBSERVATIONS AND DATA REDUCTION

UBVRI observations of NGC 129 were obtained at the Palomar 60" telescope on the night of 1993 July 24. The detector was a Tektronix 1024x1024 CCD with 24pm pixels, resulting in a field of ~ 6.5x6.5 arcmin. A second set of UBV CCD observations were obtained on the night of 1994 January 16. The detector in this case was a Tektronix 2048x2048 CCD, providing a ~ 13x13 arcmin field of view. However, because the physical size of the chip is larger than the largest available V filter, the usable field was only ~ 13x 13 arcmin. The cluster spans a much larger region of the sky and hence on] y the central regions were observed. Long and short exposures were taken with each filter in order to increase the dynamic range over which accurate magnitudes and colors could be determined and to provide an estimate of the internal photometric errors. The bias subtraction and flat-fielding of the images were done using standard routines in the IRAF data reduction package. For the 1993 July data, instrumental magnitudes were obtained using the DoPHOT photometry reduction package (Schecter, Mateo, & Saha 1993). For the 1994 J anuary observations, instrumental magnitudes were obtained using the DAOPHOT and ALLSTAR (Stetson 1987,1994) stellar profile-fitting routines. Both nights were photometric.

Aperture corrections were determined for each image by performing aperture photometry on several of thc brightest, most isolated stars in the field. The scat ter in the aperture corrections indicates that, in the mean, the aperture corrections arc accurat c to better than 0.005 mag in each filter and that the aperture corrections for individual stars should bc accurate to within 0.015 msg.

Several of the UBVRI standard stars from the listof],ando]t(1992) were also observed on both nights in order to transform the data onto the st andard systcm. Aperture photometry was obtained for the standard stars in exactly the same manner as the aperture photometry of the stars used to determine the aperture corrections for the cluster data. Once the extinction and transformation coefficients were determined, the standard star instrumental magnitudes were transformed to the standard system, in order to investigate the accuracy of the transformations. The standard deviation of the scatter of the standard star magnitudes and colors about their published values is $\sim$ 0.02 mag in all filters. This scatter increases slightly for the reddest stars ((B — V) > 2.0 mag) in the data for the night of 1993 July 24, but this should not affect the distance determination of NGC 129, since the stars of interest for this purpose arc much bluer.

A comparison of the B and V magnitudes derived for the two data sets for different nights shows that the photometric zero-points agree to within $\pm$0.02 msg. Wc have therefore averaged the magnitudes for the stars which were observed on both nights, with the individual magnitudes being weighted according to the errors output by the prof]lc-fitting photometry routines. Some stars have only a single observation in B and V because the field observed on the second night was larger than the field observed on the first night and because the photometry on the second night dots not go as deep.

The U data from the two nights shows a large systematic difference in the derived photometric zero-points (AU $\sim$ 0.1 mag). An external comparison with other photometry (sec §3) indicates that the data from the night of 1994 January 16 is on the standard UBV systcm, Therefore the U data for the night of 1993 July 24 were transformed to the zero-poi]lt adopted for the 1994 January 16 data. The U magnitudes for the stars observed on both nights were then averaged together in the same fashion as the BV data, in order to reduce the random photometric errors.

An earlier set of UBV data had been obtained on the night of 1992 October 2. The combined data from the aforementioned two nights were used to place these data on the standard systcm. The magnit udcs from this night were then averaged in with the previous nights' data to produce a single photometric list. Once again, the field observed was offset from the other two nights, with the result that a region of ~ 10x I 1 arcmin was surveyed over the three nights. Figure 1 shows a B-band gray scale image of the region observed.

Figure 2 shows the resulting color-magnitude diagram (CMD) for NGC 129. The main-sequence is clearly visible, although at V > 16 mag, there appears to be a significant population of field stars. The width of the main-sequence is larger than expected from the size of the photometric errors. While this may be the result of a number of different effects, wc argue below in §4 that it is most likely duc to the existence of differential reddening across the cluster.

III. COMPARISON WITH OTHER PHOTOMETRY

Photoelectric UBV observations of some of the brighter stars in NGC 129 have previously been published by Arp, Sandage & Stephens (1959), Hoag et al. (1961), and Turner, Forbes & Pedreros (1992). The external accuracy of our photometry can be estimated by comparing our magnitudes and colors to these previous studies. The photoelectric observations include some stars which arc outside the field of our CCD observations, and therefore could not be included in the comparison. Furthermore, some of these stars were found to be double as judged by the profile-fitting photometry routines used in the present study. Hence, these stars have also been excluded from the comparison.

Table 2 shows a comparison of our U BV photometry with those of the three previously published st udics. Wc find the best agreement bet wccn our photometry and that of Turner et al. (1992). Figures 3a-c show the comparison of the V magnitudes and (B – V) and (U – B) colors for the two sets of data. There is some indication that the scatter between the two sets of V magnitudes increases for the fainter stars, but there dots not appear to be any scale error, which might otherwise indicate a non-linearity in the photometry. The V magnit udes and (B – V) colors of Hoag et al. (1961) arc also in good agreement with those presented here.

There dots appear to be a small zero-point difference between our (B – V) colors and those of Arp et al. (1959). The difference is in the sense that the Arp et al. (B – V) colors are bluer than our colors by 0.046+ 0.012 msg. lhis difference is in the same sense as that found by Turner et al. (1992) in their comparison with the Arp et al. data. This is not surprising since *the (N--V)* colors presented here agree with those of Turner et al. and largely the same set of stars is used in comparing the three sets of photometry.

'J'able 2 shows that our (U – B) colors arc systematically Mucr than those of the other studies. Wc have therefore chosen to apply a correction of +0.02 mag to our (U – B) colors, which brings thcm into good agreement with those of Turner ct al. (1992) and Hoag ct al. (1961). The Arp et al. (1959) colors appear to be bluer still but the scatter between their (U – B) colors and ours is much larger than for the other studies.

in summary, it appears that the photometry of Turner et al., Hoag et al., and data presented in this paper arc on the same BV system, while the (H – V) colors of Arp et al. arc too blue by ~ 0.04 msg. 'J'here also dots not appear to be any magnitude or color dependent differences between any of the different sets of photometry. Therefore, wc arc confident that our BV photomet ry is' on the standard systcm. Our (U – B) zero-point originally disagrees with previous studies by 0.02 rnag. Wc have adopted their zero-point and carry this assumption through as a potential source of systematic error in the final uncertainty in the distance modulus.

'1'here is no previously published RI photometry for the stars in NGC 129 and hence wc arc unable to make a direct check of the external accuracy of our red photometry. However, the cluster NGC 7790 was also observed on the night of July 24/25, 1993, and a comparison of our (V — R) and (V — 1) colors with those of the secondary standard photometric sequences of Christian et al. (1985) shows good agreement bet wccn the two sets of data. The photometry of NGC 7790 will be presented in the second paper in this series (Hill ct al. 1994).

We present in 'J'able 3 the photometry for those stars which have previously published photoelectric photometry. The complete set of UBVRI photometry will be made available on the AAS CD-ROM series.

IV. THE REDDENING TOWARD NGC 129

The amount of interstellar reddening toward NGC 129 can be determined from the UBV data by using the standard technique of plotting the data in a two-color [(U – B) vs. (B – V)] diagram and calculating the color excess, E(B — V), from the displacement of the stars along the reddening trajectory in this diagram. In the simplest application of this method, a color excess is determined for each star and the mean color excess for the cluster is found by calculating the average of these values.

in the case of NGC 129, the width of the main-sequence in Figure 2 suggests that there is significant differential reddening towards the stars in the c.luster. The stars denoted by filled circles in the figure typically have errors of less than 0.035 mag in each of V and (B – V). These errors arc not large enough to produce the observed Inain-sequence color width, which is several tenths of a magnitude. This first impression is quantitatively reinforced by the two-color diagram displayed in Figure 4. In this figure, only those stars which have errors in each of V, B and U of less than 0,04 mag have been plotted. Also, in order to reduce the confusion duc to the increasing presence of field stars at fainter magnitudes and redder colors, cutoffs at $V \lesssim 16.5$ mag and at $(H - V) \lesssim 1.2$ mag were applied. The error bars in the figure show the photometric errors associated with each star. As in the case of the CM]], the width of the sequence in the t we-color diagram appears to be larger than can be explained by photometric errors alone. Previous investigations (Arp et al. 1959, Schmidt 1980, Turner et al. 1992) also concluded that differential reddening was present.

The precision of the photometric data permits us to deredden each star individually. The resulting reddening-corrected CMD should have a much tighter main-sequence than would be obtained if a mean color excess were applied to all of the stars in the cluster. This in turn should lead to a more precise estimate of the distance from the main-sequence fitting technique.

In practice, however, there are noteworthy problems in calculating the color excess for certain stars in Figure 4. The first problem arises because the reddening trajectory in the two-color diagram can intersect the intrinsic two-color curve for main-sequence stars in more than one place, giving rise to an ambiguity in the calculated color excess. It may be possible to choose between the allowed values of the color excess if other information is available (e.g., if the spectral t ype of the star is known or if the color excess is a priori expected to be within some specified range). A second problem is encountered specifically for stars with intrinsic. colors in the ranges $-0{,}05 \lesssim (B - V)_{\circ} \lesssim 0.20$ and $0.40 \lesssim (B - V)_{\circ} \lesssim 0.70$; for these stars the slope of the reddening trajectory is close to parallel to the intrinsic two-color sequence. Thus, small photometric errors can result in very large reddening uncertainties. These problems arc discussed in dct ail in the appendix.

We have therefore chosen to deredden the cluster stars in two different ways and to determine a distance to the cluster from each of the resulting dereddened CMDs. The first method is to calculate the mean color excess for the cluster and simply deredden each star in the cluster by this mean value. In order to eliminate most of the field stars from calculation of the mean color excess, the sample was restricted to the prominent ridge of stars in Figure 4. The two-color diagram for this subset of 122 stars, most of which will be c.luster members, is shown in Figure 5. Unambiguous color excesses (see the appendix) can be found for 83 of these stars by projecting them back onto the intrinsic two-color curve along a line of slope 0.70. The mean color excess calculated from these stars is $E(B-V) = 0.57 \pm 0.01$ mag. The ratio of the color excesses, $E(U - B)/E(B - V)$, used here is smaller than the value of 0.76, which was adopted by Turner et al. (1992). We find that the latter value of 0.76 results in a poor fit to the cluster data over the range $-0.10 \leq (B-V)_0 \leq 0.20$ msg. Unless a smaller value is used, the intrinsic, curve passes below the data over this range, after the data is corrected for the mean extinction.

An estimate of the mean reddening to the cluster can also be made from the BVI data. The method is the same as that used to determine the reddening from a set of UBV data. The reddening is found by plotting the stars on a two-color diagram (in this case $(B-V)$ vs. $(V-1)$) and then projecting these stars along the reddening trajectory back onto the intrinsic curve for unreddened stars in this diagram. Using the reddening law of Dean, Warren, & Cousins 0978) and the intrinsic colors of Walker (1985a), the mean color excess is calculated to be $E(B-V) = 0.584{:}0.05$ msg. The larger uncertainty occurs because the reddening trajectory and the intrinsic tow-color relation are c1ose to parallel in the $(B-V)$ vs. $(V-1)$ two-color diagram for all colors. Nevertheless, this result confirms our earlier conclusion that the mean color excess for NGC 129 is $E(B-V) = 0.57 \pm 0.01$ msg.

Figure 6a displays the reddening-corrected CMD for NGC 129, where a mean color excess of 0.57 mag has been used to deredden all the stars. A value of $R = 3.2$ was used for the ratio of total-to-selective absorption. The stars in Figure 6a are the same as those which appear in Figure 5 and hence should be primarily cluster members. The CMD shows a smoothly continuous main-sequence, although there are clearly some field stars present at magnitudes fainter than V = 12.5 msg.

A second method of accounting for the reddening is to individually deredden those stars for which a reliable color excess can be calculated. In this case, it is not necessary to restrict the sample to the stars which appear to be cluster members duc to their proximity to the main ridge of stars in Figure 4. Unambiguous color excesses can be calculated for 119 stars in this manner. These stars and their color excesses arc listed in ‘J’able 4. The details of the dereddening procedure arc discussed in the appendix.

Figure 6b shows the reddening-corrected CMD for NGC 129 for the stars which can be dereddened according to their individual colors. The upper main-sequence in Figure 6b is much tighter than in Figure 6a but there is a large gap in the main-sequence in the color range $-0.05 \leq (B - V)_o \leq 0.2$ mag, due to the difficult y in assigning an unambiguous color excess to stars in this range (see appendix). The main-sequence appears again ill the color range $0.40 \leq (B - V)_o \leq 0.60$ mag, but is somewhat confused with field stars. The stars with $(B - V) \geq 0.70$ mag arc field stars.

Several previous estimates of the reddening toward NGC 129 have been made. Arp et al. (1959) found a mean colour excess of $E(B - V) = 0.53$ mag from UBV photometry. Considering that Arp's $(B - V)$ colors arc systematically bluer by 0.046 mag than those presented here, the color excess difference (–0.04 mag) is entirely consistent.

l’helps and J ants (1994) have also recently presented UBV photometry for NGC 129. “J’heir data were calibrated using the photoelectric photometry of Hoag et al. (1961), which agrees well with the photometry presented here. The mean extinction found for stars with $(B - V) < 0.70$ mag is $E(B - V) = 0.57$ mag, which agrees well with our result. Turner et al. (1992) do not derive a value for the mean color excess of NGC 129. However, an examination of their Figures 3 and 5 show that our value of $E(B - V) = 0.57$ mag is also entirely consistent with their data.

Schmidt (1980) has obtained four-color and $H\beta$ photometry of stars in NGC 129 and finds a mean color excess of $E(b - y) = 0.442$ msg. Applying Crawford's (1975) conversion, $E(b - y) = 0.74E(B - V)$, results in an equivalent color excess of $E(B - V) = 0.60$ mag, which is again in good agreement.

In summary, we find a convergence in several different estimates of the reddening toward NGC 129. The color excess of $E(B - V) = 0.57 \pm 0.01$ mag (based on a sample of 83 stars) found here is representative of these estimates and we adopt it as the mean value for the interstellar reddening for stars in the cluster.

V. THE DISTANCE TO NGC 129

The distance to NGC 129 was determined by the main-sequence fitting technique for both sets of dereddened data. The ZAMS of Turner (1976, 1979) was adopted. in order to make the fit, however, it is necessary to restrict the sample to those stars which are thought to be main-sequence cluster members. We consider first the case in which the stars were dereddened by the mean value for the cluster (see Figure 6a). Figure 7a shows the CMD for the subset of stars judged to be main-sequence cluster stars (compare with Figure 6a).

Since the observed color width of the main-sequence is primarily due to differential reddening, it would be incorrect to try to fit the ZAMS to the lower envelope of the observed main-sequence. The stars forming the lower envelope are more likely to have lower reddening than the mean for the cluster. Since the cluster data have been dereddened by the mean color excess, it is more appropriate to fit the ZAMS to the middle of the cluster main-sequence. However, the upper main-sequence contains stars which have evolved away from the ZAMS and hence the inclusion of these stars would systematically bias the distance modulus, Therefore only stars with $V_o \geq 11.0$ mag were used in calculating the distance modulus. A distance modulus was calculated for each of the 87 stars which satisfy this criterion and the mean distance modulus for these stars is $V_o - M_v = 11.08 \pm 0.05$ mag (where the error quoted is the standard error). In order to test whether or not a bias was introduced by including evolved stars at the bright end of the magnitude cutoff, the distance modulus was recalculated for 72 stars with $V_o \geq 12.0$ mag. The distance modulus obtained in this manner is $V_o - Mv = 11.05 \pm 0.05$ mag. We therefore conclude that the stars in the magnitude range $11.0 \leq V_o \leq 12.0$ have not evolved significantly from the ZAMS since the two values of the distance modulus agree to within the errors and the sense of the change is opposite from that which would occur if the bias existed. We therefore adopt $V_o - M_v = 11.08 \pm 0.05$ mag as our best estimate of the distance modulus for the case in which the stars were dereddened by the mean value of the color excess for the cluster.

Figure 7b shows the CMD for the stars which were dereddened individually. Only those stars thought to be main-sequence cluster members are plotted (compare with Figure 6b). Choosing only stars with V_o >11.0 mag, as above, results in a distance modulus of $V_o - M_v = 11.08 \pm 0.04$ mag, based on 59 stars. However, a closer look at Figure 7b suggests that the stars in the magnitude range $11.0 \leq V_o < 12.0$ mag may be evolved stars. When the distance modulus was recalculated for the 47 stars with $V_o \leq 12.0$ mag, a new value of $V_o - Mv = 11.11 \pm 0.04$ is obtained. We adopt this as our best estimate of the distance modulus for the case in which the stars were dereddened individually.

There is no compelling reason to prefer one value of the distance modulus over the other. The two results agree to within the formal errors. We therefore take a simple average of the two results and conclude that the distance modulus for NGC 129 is $V_o - Mv = 11.10 \pm 0.04$ msg.

The formal errors obtained from the main-sequence fitting procedure are quite small. However, the true uncertainty in the distance modulus is larger because of the possible presence of systematic errors. The largest potential source of systematic error is in the choice of the reddening law. In particular, the ratio of total-to-selective absorption used here, $A_v = 3.2$, is probably uncertain at the level of ± 0.3. Since the observed V magnitudes are corrected by the factor $A_V \times E(B - V)$, the derived intrinsic V_o magnitudes could be systematically in error by as much as +0.17 mag, which translates directly into an error of the same size in the distance modulus.

A second source of systematic error arises in the choice of the ZAMS. If the ZAMS of Schmidt-Kaler (1982) is adopted, the best fit distance modulus is increased by 0.10 msg. We have adopted Turner's (1976, 1979) because it has been used by Turner et al. (1992) and by Walker (1985ab, 1987ab) in his studies of the southern Cepheid clusters. This choice facilitates a direct comparison with most of the recent efforts to obtain distances to the Galactic clusters containing Cepheids.

Systematic errors in the photometry are unlikely to be large due to the good agreement between independent observations of the bright stars in NGC 129 (see §3). However, systematic errors in the distance modulus could be introduced in the selection of the stars used in calculating the distance modulus. In particular, the inclusion of field stars or the exclusion of true cluster members could bias the distance modulus. The magnitude of this possible source of error was tested by changing the sample of stars used in the calculation of the best fit distance modulus. Large and improbable changes in the choice of main-sequence stars are required to change the distance modulus by more than ±0.05 msg. The (relatively) large number of stars used to estimate the distance modulus is the reason that the inclusion of field stars or the exclusion of cluster members has only a small effect on the estimated distance modulus.

Previous estimates of the distance modulus of NGC 129 range from 10.80 (Hoag & Applequist 1965) to 11.54 (Cox 1979). However, the most recent estimates (including the present study) have converged to values near $(V_o — M_v) = 11.10$. Turner et al. (1992) find a distance modulus of 11.11 ± 0.02 and Phelps & Janes (1994) find $(V_o - Mv) = 11.20$. However, Phelps & Janes used the Schmidt-Kaler (1982) ZAMS which, as demonstrated above, results in a systematic difference in the estimate of the distance modulus of +0. 1 msg. This accounts for the entire difference in the derived distance moduli.

Schmidt (1980) derived a distance modulus of 10.93 ± 0,19 for NGC 129 from four color and H/3 photometry; a reanalysis of his data by Balona and Shobbrook (1984) yields a distance modulus of 11.074:0.14. Turner et al. (1992) have suggested that the Hβ 1 uminosities of several of the stars may be contaminated by the light of unresolved companions and that the distance modulus might be as large as 11.20 ± 0.04.

In considering these recent estimates of the distance modulus of NGC 129, we find that our estimate of the modulus of $(V_o - Mv) = 11.10+ 0.04$ mag is consistent with other results. We adopt our value as. the true distance modulus because of the large number of stars observed with high photometric accuracy in this study. This distance modulus corresponds to a distance of 16604:30 pc. The small quoted errors account for only the sources of random error in the distance estimate. The potential systematic errors are larger (0.17 mag due to uncertainty in the reddening law; 0.1 mag due to uncertainty in the ZAMS) and if they conspire to act in the same direction, could result in a systematic error of 0.27 mag in the distance modulus.

A calculation of the absolute magnit udc of 1)1, Cas requires the mean magnitude, < V >, and color excess E(B – V) for the star. Schaltenbrand & Tammann (1971) calculate an intensit y mean magnitude of < V >= 8.94 mag, while Moffett & Barnes find < V >= 8.97 msg. We adopt here the simple mean of these two results, $< V > = 8.96$ 3:0.02 msg. Assigning a color excess to DL Cas is more problematical, duc to the presence of differential reddening within the cluster. One possible choice is to adopt the mean color excess for the cluster, $E(B - V) = 0.57 \pm 0.01$ msg. However, a more appropriate estimate of the error in this case is the standard deviation about the mean, which reflects the scatter duc to both photometric errors and differential reddening. The color excess assigned to DL Cas in this way is 0.57 ± 0.04 msg. Using this value of the color excess and the distance modulus derived above, the absolute magnitude of DL Cas is $< Mv > = -3.96 \pm 0.14$ msg.

A second possibility is to adopt the color excess of the nearest star for which an unambiguous color excess has been determined. The nearest star (#/330) has a color excess of 0.66 ± 0.01 mag and lies ~ 20 arcsec from the Cepheid. However, it appears that the amount of reddening towards stars in the vicinity of DL Cas is quite variable, Figure 8 shows a plot of the reddening towards stars in the fiels of NGC 129. The location of DL Cas is marked by a plus sign. It is clear from the figure that stars in the vicinity of DL Cas arc reddened by widely varying amounts. For the 8 stars which lie within 90 arcsec of the Cepheid and have measured color excesses, wc find a mean of color excess of $E(B - V) = 0.58+ 0.02$ msg. The standard deviation about this mean is 0.05 mag and the individual reddenings range from 0.51 mag to 0.66 msg. Once again taking the standard deviation to be a better estimate of the true uncertainty, the color excess for the Cepheid estimated in this manner is 0.58+ 0.05 msg. We adopt this value as our best estimate of the color excess of DL Cas, and hence our best estimate of its absolute magnitude is $< M_v > = --4.00 \pm 0.17$ msg. We note once again, that systematic errors in the distance modulus of NGC 129 could be as large as ± 0.27 mag, which would propagate directly into an error of the same size in the absolute magnitude of DL Cas. Also, wc have not included any correction for the unresolved companion discovered by Harris et al. (1987).

Several attempts have been made to estimate the color excess of 1)1, Cas from photometry of the Cepheid itself (eg. Fernie 1963, 1990, Parsons & Hell 1975, Harris 1981). These studies typically find smaller values of $E(H - V)$ than wc have adopted here (e.g. Fernie (1990) most recently finds $E(B - V) = 0.533$:0.02 mag). However, these investigations often usc different photometric systems and may be subject to large systematic errors duc to the uncertaint y in the intrinsic colors of Cepheids (M adore & Freedman 1991). The color excess of DL Cas remains the largest source of uncertainty in the determination of its absolute magnitude.

The absolute magnitude of DL Cas has recently been determined by Turner et al. (1992), who find $< M_V > = -3.80 \pm 0.05$ msg. However, they have used a much smaller color excess for DL Cas (0.51 ± 0.01 mag), which they determine from only those nearby stars with small reddening. They argue that the larger reddening values for other nearby stars (mostly B-type stars) arc duc to either excess circumstellar reddening or rotation. However, wc find no such trend toward higher color excesses for the brighter (B-type) stars in the cluster. The difference between the absolute magnitude of DL Cas derived by Turner ct al. and that derived here is duc to the different reddening correction applied to the star.

V. CONCLUSIONS

We have presented UBVRI CCD data for stars lying in the direction of the Galactic open cluster NGC 129, which contains the Cepheid DL Cas. The BV photometry is on the same system as that of Turner et al. (1992) and Hoag et al. (1961), while there is a small zero-point offset between our (B – V) colors and those of Arp et al. (1959) in the sense that the Arp ct al. colors arc too blue by 0.046 msg. Relative to Turner et al. and Hoag et al., our (U – B) colors arc systematically too blue by 0.02 mag, and hence wc have corrected our (U – B) colors by this amount. The RI photometry presented here is the first such data for stars in the NGC 129 field.

The (U – B) vs (B – V) two-color diagram for the bright main sequence stars in NGC 129 yields a mean color excess for the cluster of $E(B-V) = 0.57 \pm 0.01$ msg. This value is in excellent agreement with the mean color excess of the cluster determined in several other studies.

The width of the main-sequence in both the CM 1) and two-color diagram indicate that the stars in the field of NGC 129 suffer from a significant amount of differential reddening. The high accuracy of our photometric data permit us to attempt to deredden the stars individually. in doing so, wc note that stars with intrinsic colors in the ranges $-0{,}05 \leq (B-V) \leq 0.20$ mag and $0.40 \leq (H-V) \leq 0.70$ mag generally have large uncertainties in their individual color excesses because the reddening trajectory in the two-color diagram is nearly tangent to the intrinsic sequence or may intersect it at more than one point.

Main-sequence fitting of the ZAMS to the upper main-sequence of NGC 129 yields a distance modulus of 11.10 ± 0.04 mag, corresponding to a distance of 1660 ± 30 pc. However, the systematic errors in the distance modulus may be as large as ~ 0.27 mag. Our adopted distance implies a mean absolute magnitude of $< M_V > = -4.00 \pm 0.17$ mag for DL Cas. The large uncertainty in $< M_V >$, compared to that for the distance modulus, arises because of the large uncertainty in the reddening of DL Cas.

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Appendix A

Two serious difficulties arc encountered in the calculation of the color excess through the usc of the two-color diagram. The first problem is that the reddening trajectory for a star in the two-color diagram can intersect the intrinsic two-color curve for main-sequence stars in more than onc place, resulting in an ambiguity in the calculated color excess. If the spectral type of the star is known or if the color excess is a priori known to bc within some specified range, it may bc possible to choose between the allowed values of the color excess, but in general this type of information is not available. There is also a second problem encountered specifically for stars with intrinsic colors in the ranges $-0.05 \leq (B-V)_o \leq 0.20$ and $0.40 \leq (B-V)_o \leq 0.70$; the slope of the reddening trajectory is very nearly parallel to the intrinsic two-color sequencefor these stars. "Thus, while the colors of a star might have very small associated photometric errors, even these small errors result in very large reddening uncertainties. This problem is illustrated in Figure 9, where wc show the dereddening trajectory for a star that apparently has an intrinsic color near $(B-V)_o = 0.0$ mag. (The slope of the reddening trajectory used here is 0.70 mag. This choice for the ratio of the color excesses is justified below.) Although the photometric errors associated with this star arc small ($\epsilon_{BV} = \epsilon_{UB} = 0.014$ mag), the derived color excess remains very uncertain. These errors only restrict the color excess to be in the range $0.46 \leq E(B-V) \leq 0.66$ msg. Based on this exercise it is clear that many of the stars in the two-color diagram will not provide any distinctly useful reddening information.

The uncertainty in assigning a value of E(B – V) to many of the stars has a large effect on the dereddened CMD. To demonstrate this, it is useful to consider what happens when an attempt is made to deredden each star individually. The prominent ridge of stars in the two-color diagram (see Figure 4) represents the main-sequence of the cluster. It is apparent from a simple estimate by cyc that the mean reddening for the cluster is ~ 0.55 mag. The full color width of this ridge is lcss than ().2 mag and therefore most c.luster members should have color excesses in the range $0.45 \leq E(B-V) \leq 0.65$ mag. This is consistent with the results of Turner ct al. (1992), (Their Figure 3 shows several stars with color excesses up to 0.8 mag, but these stars arc not likely to be cluster members.) They also find a group of foreground stars with color excesses near $E(B-V) \sim 0.3$ msg. We have therefore searched for color excesses in the range

$0.2 \leq E(B-V) \leq 0.8$ msg. Figure 10 shows the dereddened CMD which results from this procedure. Stars which have only one possible value of the color excess in the searched range are plotted as filled circles. Stars which have two possible values of $E(B-V)$ are plotted twice as open circles joined by a straight line. A value of R = 3.2 was used for the ratio of total-to-selective absorption. There are very few stars in Figure 10 which have unambiguous color excesses and intrinsic colors in the ranges $-0.05 \leq (B-V)_o \leq 0.20$ and $0.40 \leq (B-V)_o \leq 0.70$. The stars that populate these parts of the cluster main-sequence have two possible values for the color excess, and in the presence of significant differential reddening, a subjective decision must be made in placing these stars in the dereddened CMD. Even if some confidence could be placed in choosing one of two possible color excesses, the fact that the intrinsic two-color curve and the reddening trajectory are nearly parallel leads to large uncertainties in the color excess, even if the photometric errors are small.

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FIGURE CAPTIONS

Fig. 1 - The color-magnitude diagram for NGC 129. The different symbols reflect the accuracy of the photometry. Filled circles represent stars with $(\sigma_V^2 + \sigma_{B-V}^2)^{1/2}$ <0.05, open circles represent stars with 0.05< $(\sigma_V^2 + \sigma_{B-V}^2)^{1/2}$ <0.10 and plus signs represent stars with $(\sigma_V^2 + \sigma_{B-V}^2)^{1/2}$ >0.10.

Fig. 2a - A comparison of our V photometry with that of Turner et al. (1992).

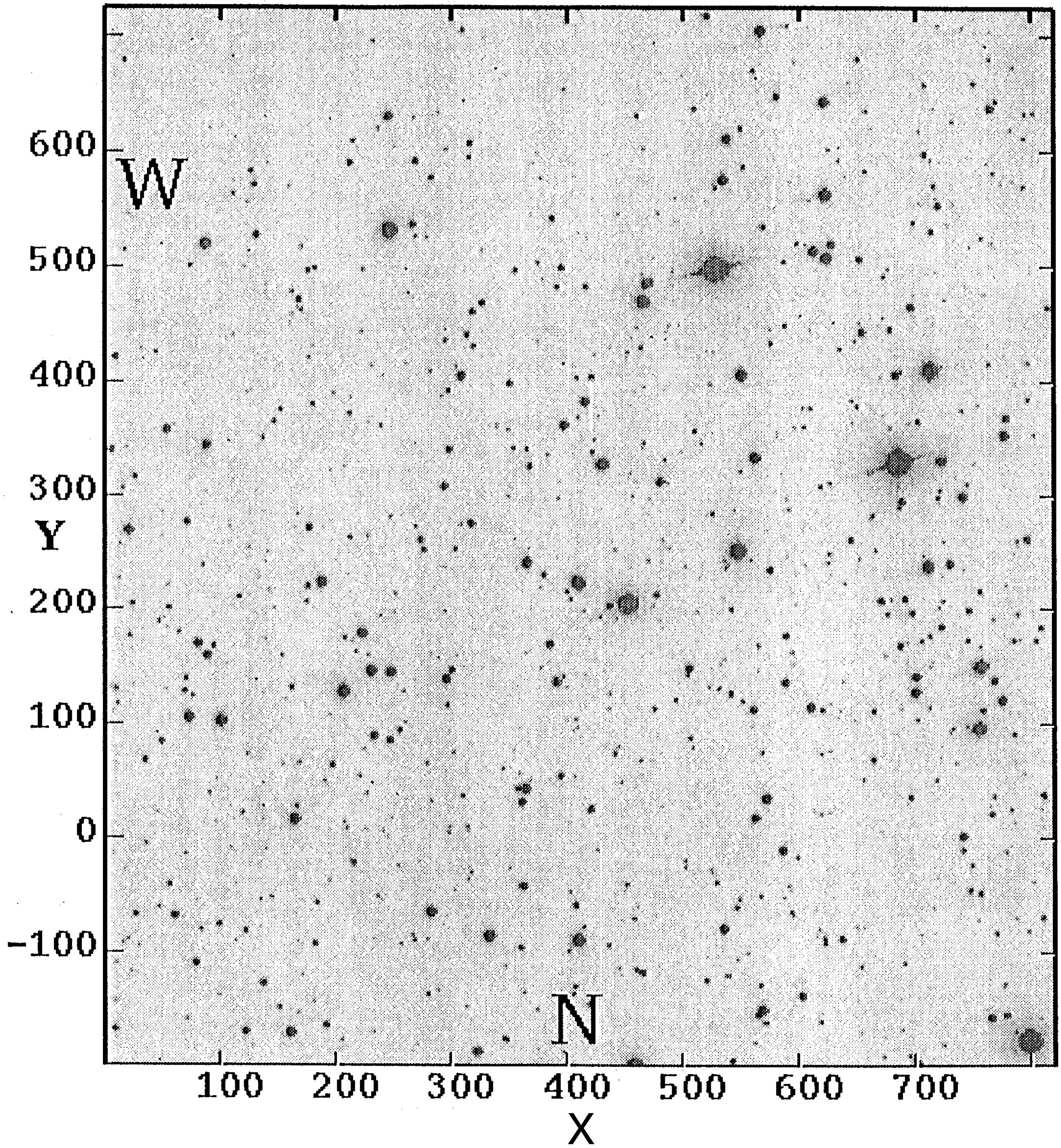
Fig. 2a - A comparison of our $(B - V)$ colors with those of Turner et al. (1992).

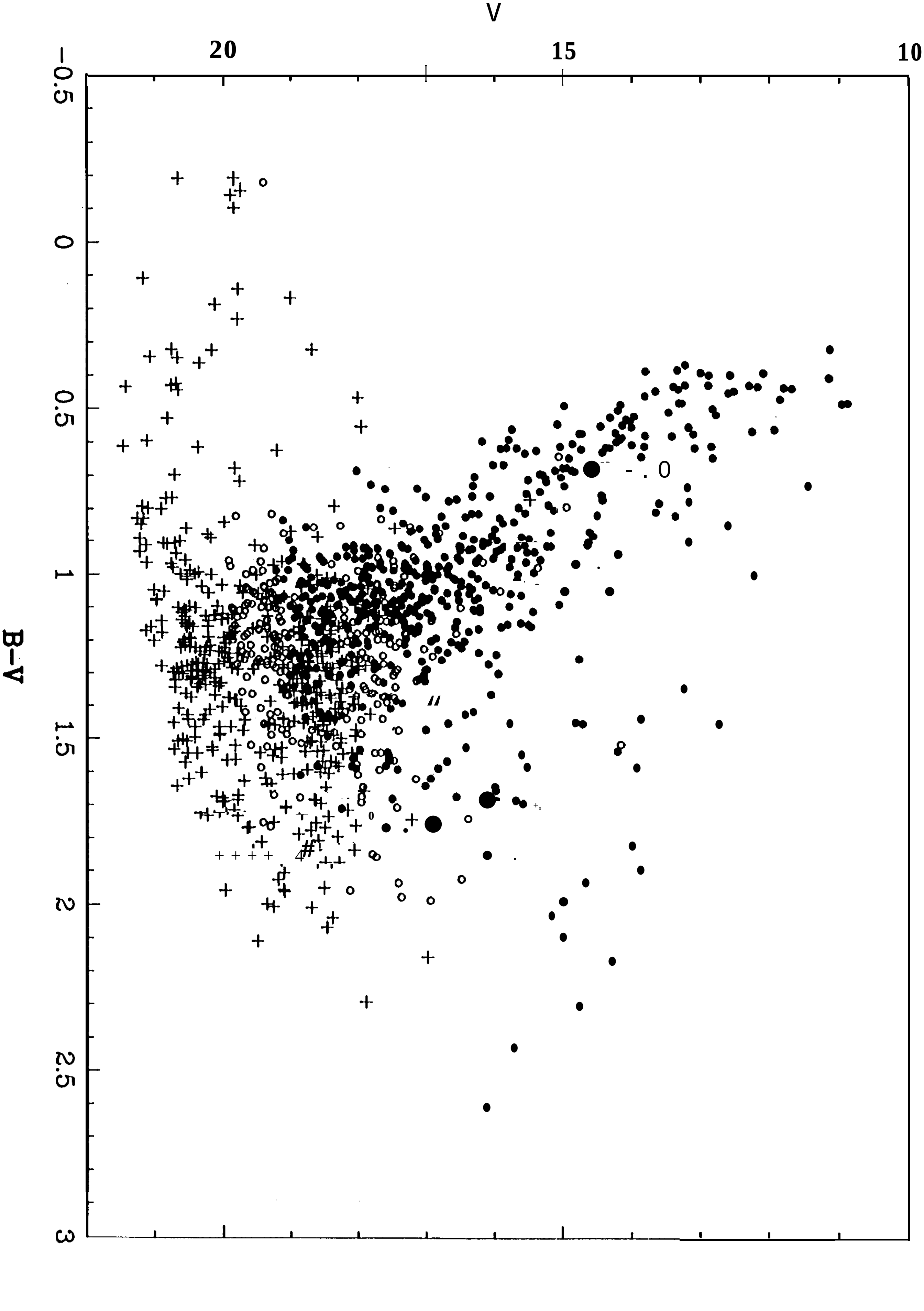
Fig. 3 – The two-color diagram for the bright stars in NGC 129. The open circles represent the observed colors of the stars, while the filled circles represent the best fit of these stars to the intrinsic two-color curve (solid line) after projecting the stars along the reddening relation given by Equation 1.

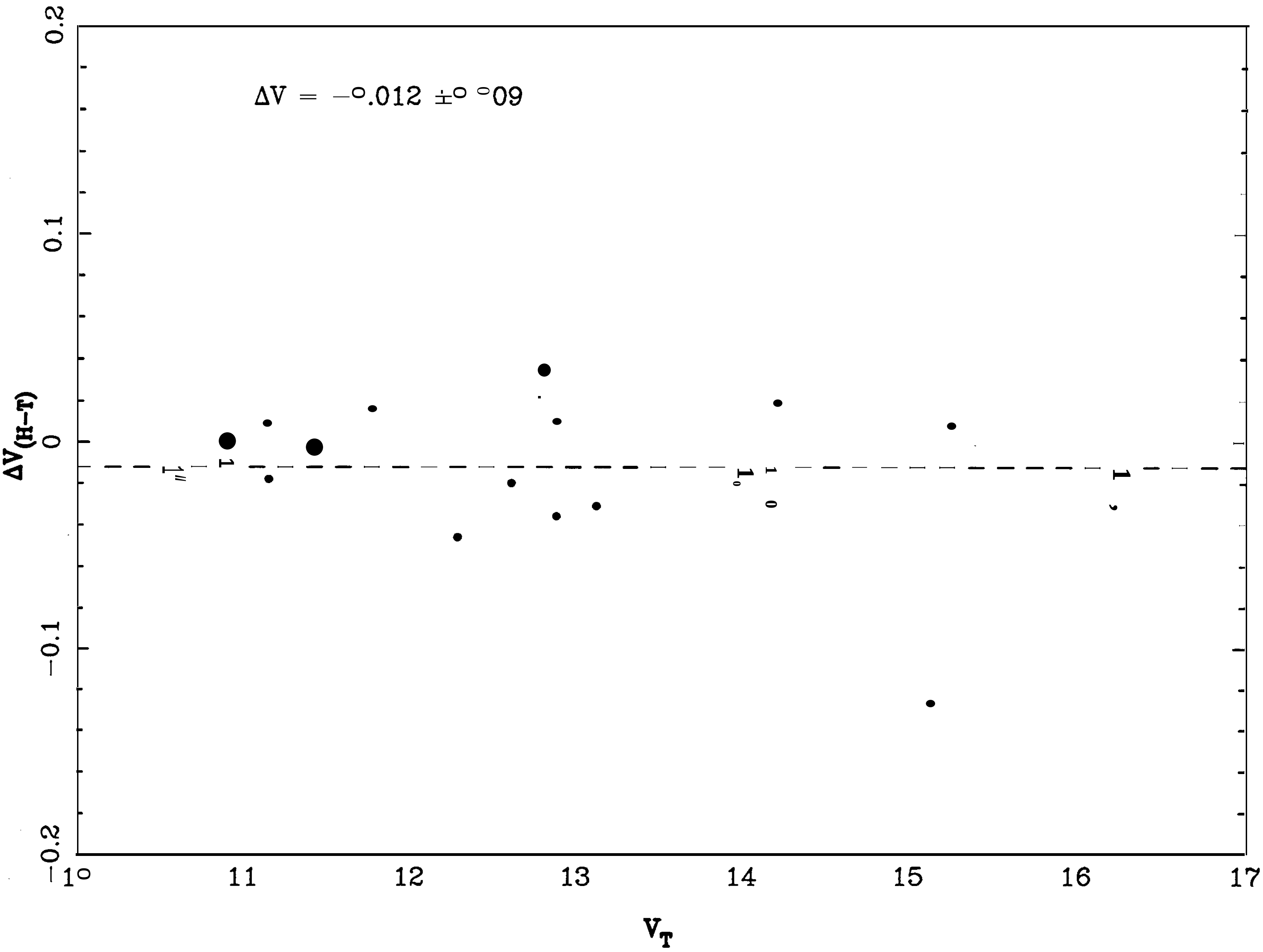
Fig. 4 – The reddening-corrected CM diagram for NGC 129. The symbols are as in Figure 1.

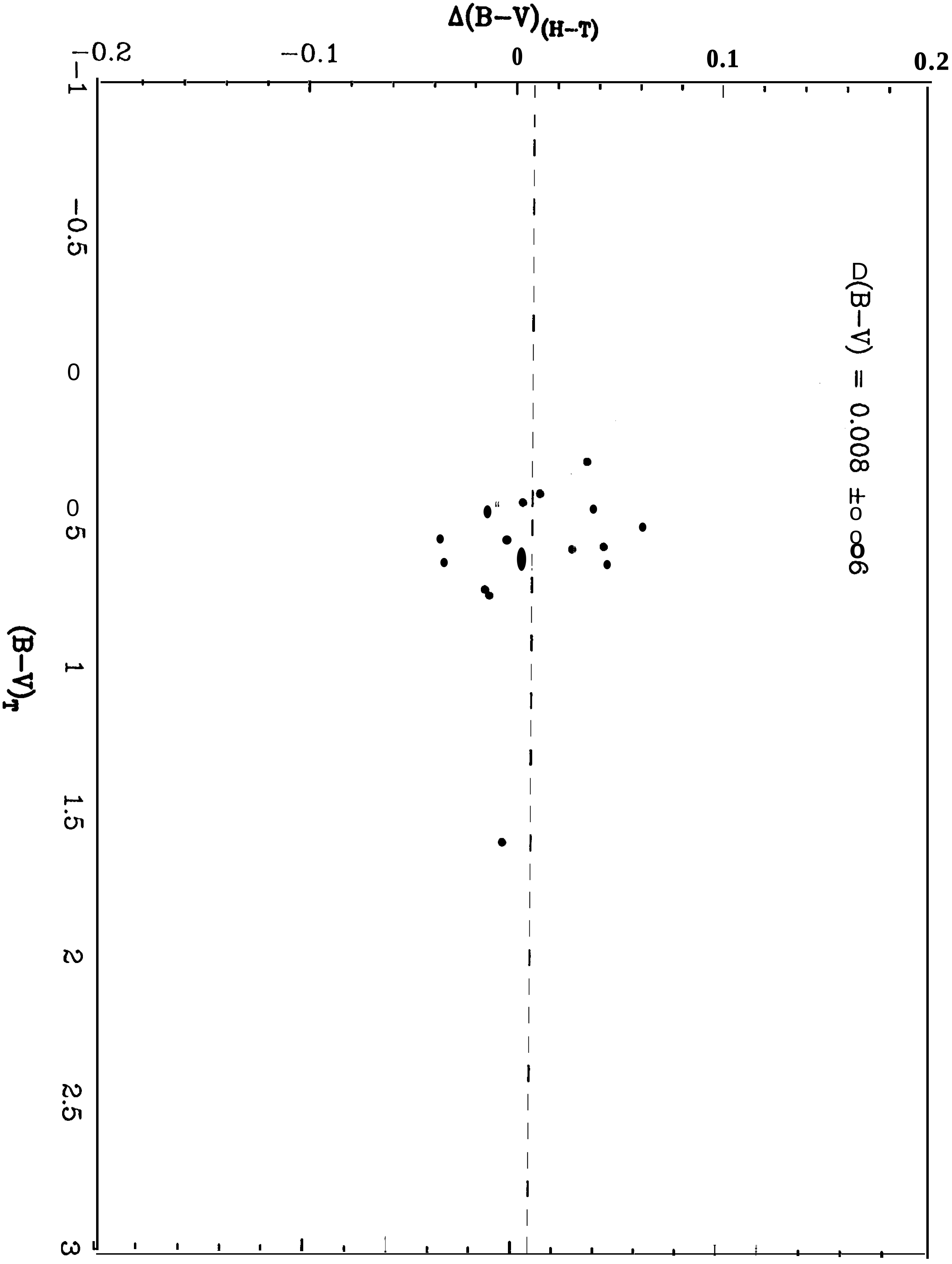
Fig. 5 – The best fit of the ZAMS to the main-sequence of NGC 129. The best fit distance modulus is $(V - M_V) = 11.25 \pm 0.10$ mag.

NGC 129 and DL Cas

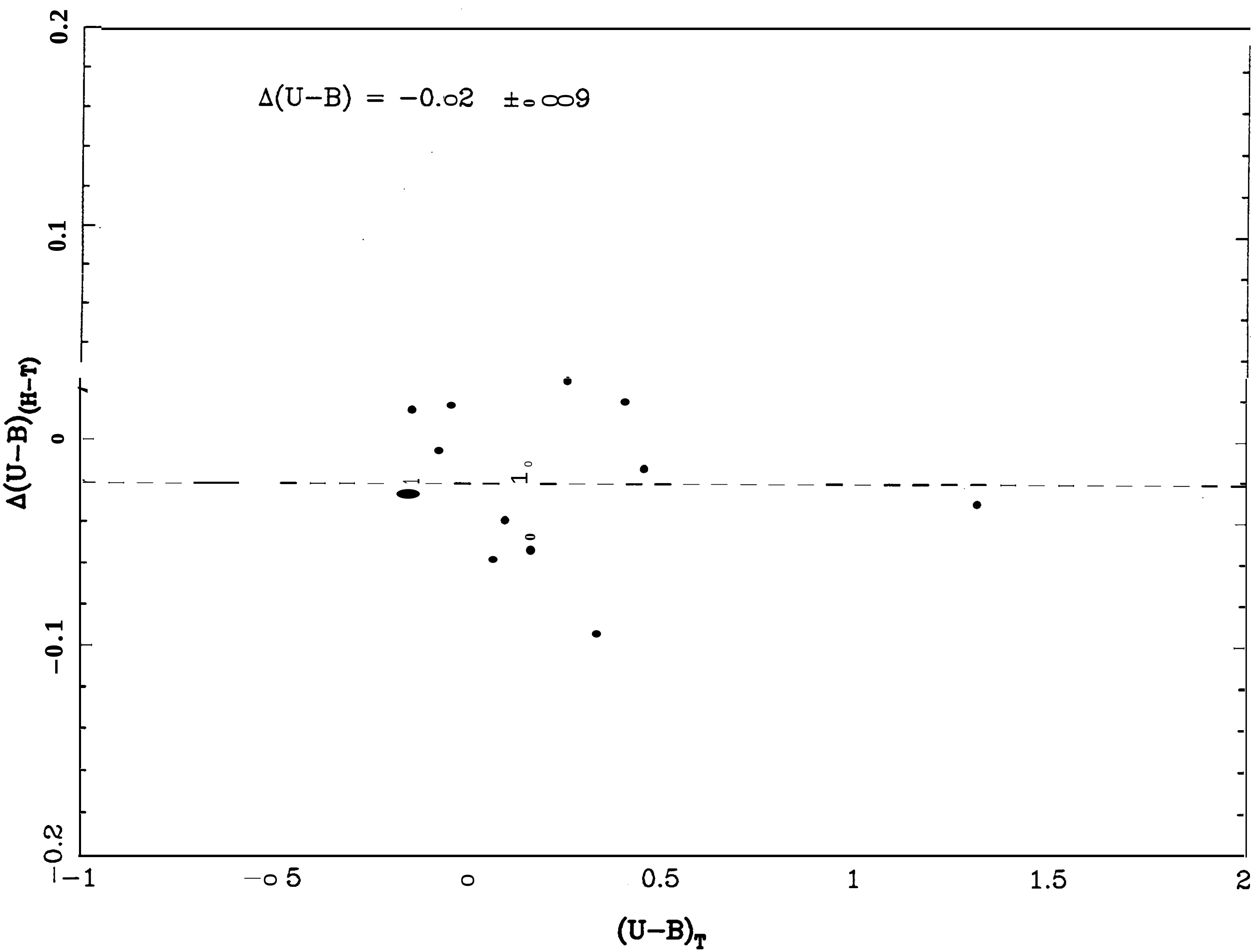



V
20
15
10
B–V
−0.5
0
0.5
1
1.5
2
2.5
3

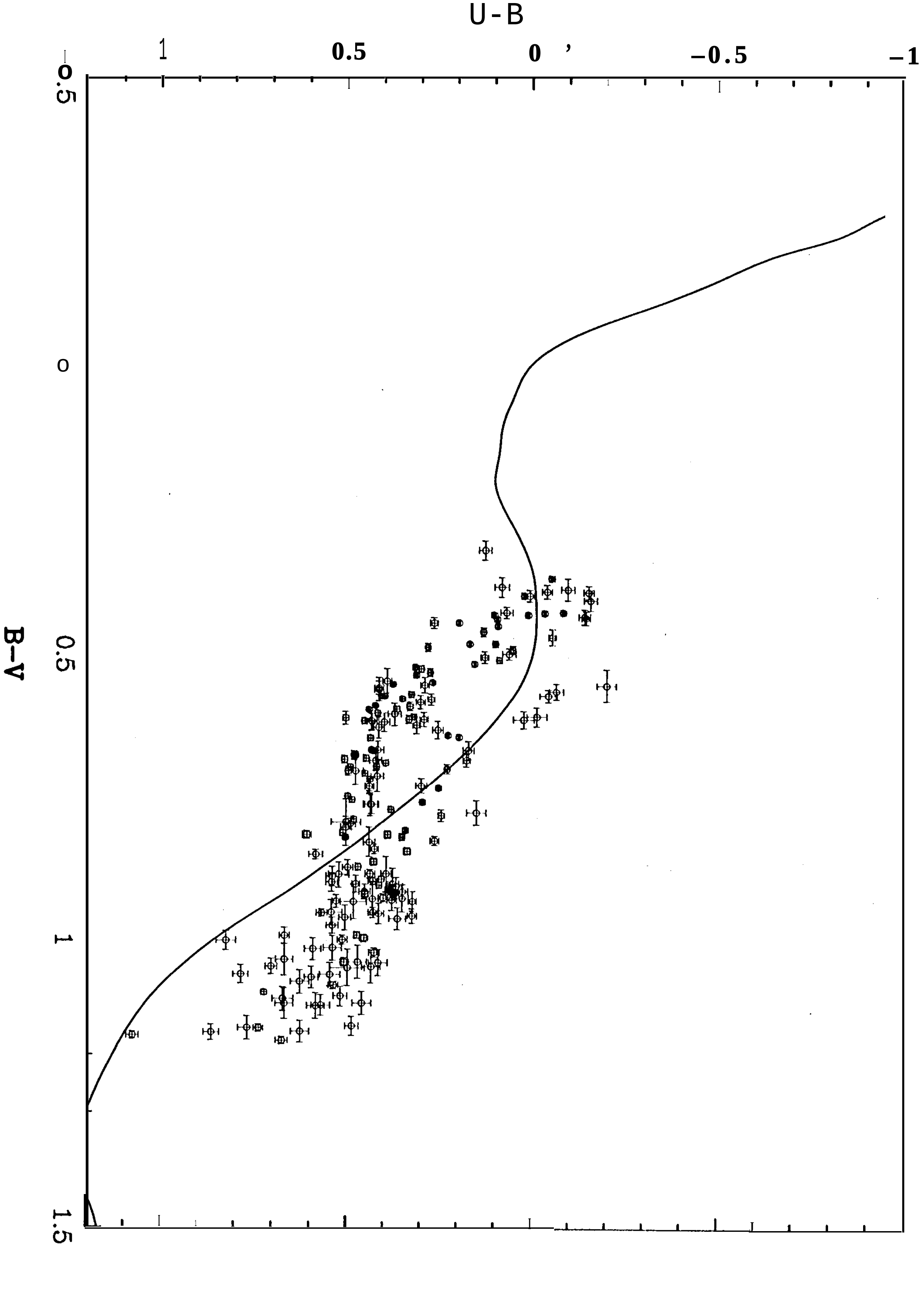

ΔV = −0.012 ± 0.009
$\Delta V_{(H-T)}$
0.2
0.1
0
−0.1
−0.2
10
11
12
13
14
15
16
17
V_T

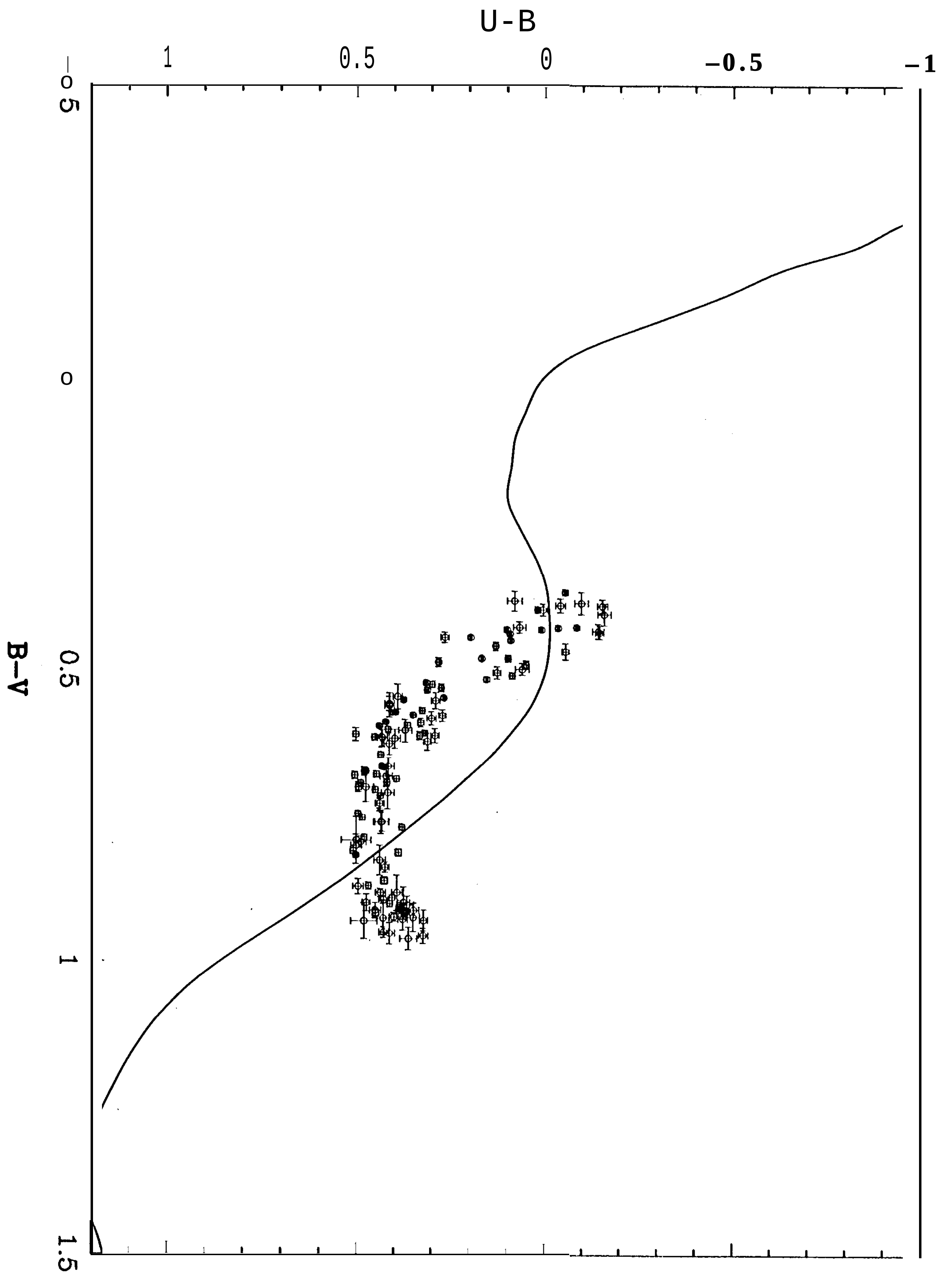


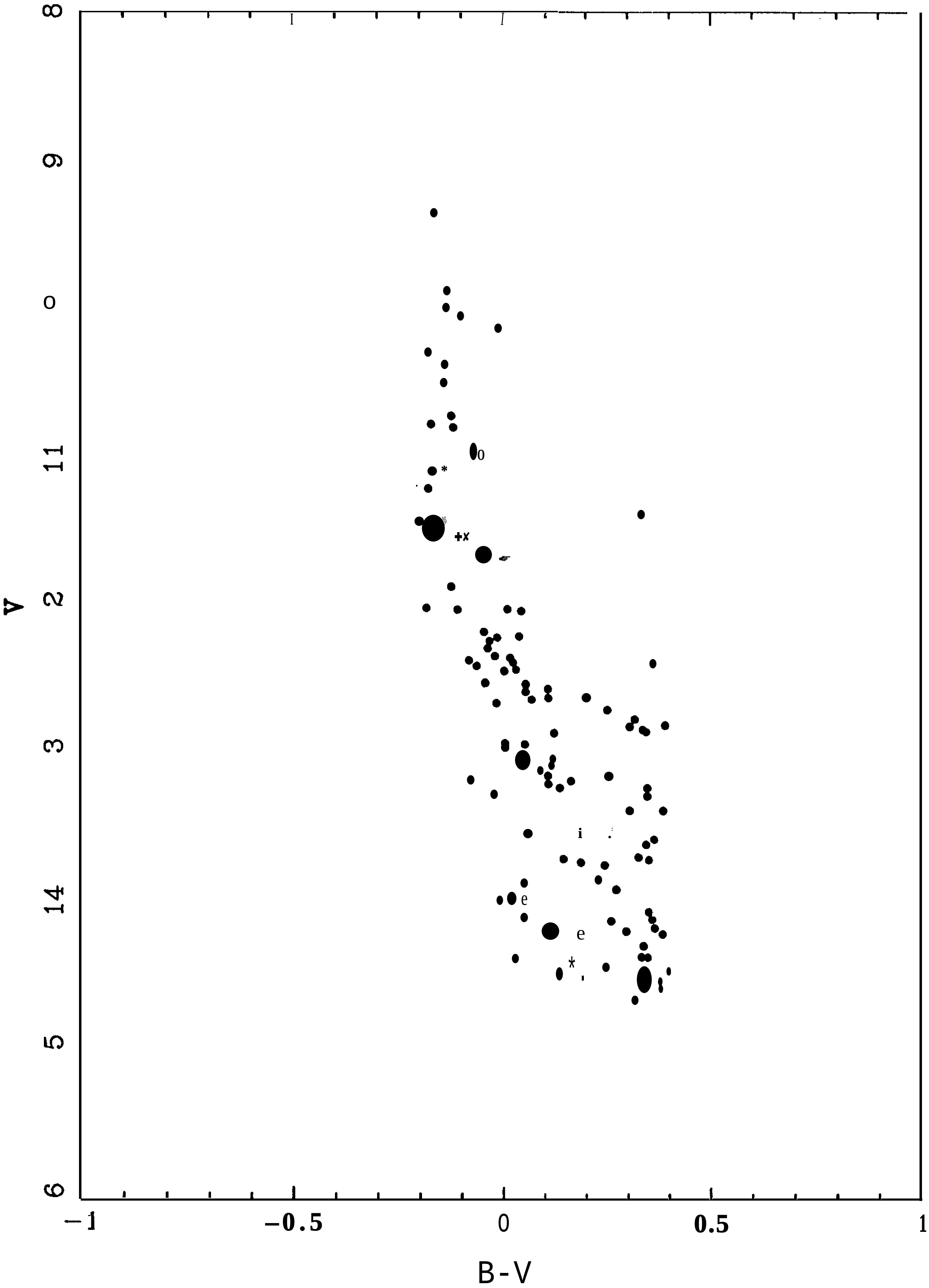
$\Delta(B-V)_{(H-T)}$
−0.2
−0.1
0
0.1
0.2
D(B−V) = 0.008 ±o oo6
−1
−0.5
0
0.5
1
1.5
2
2.5
3
$(B-V)_T$

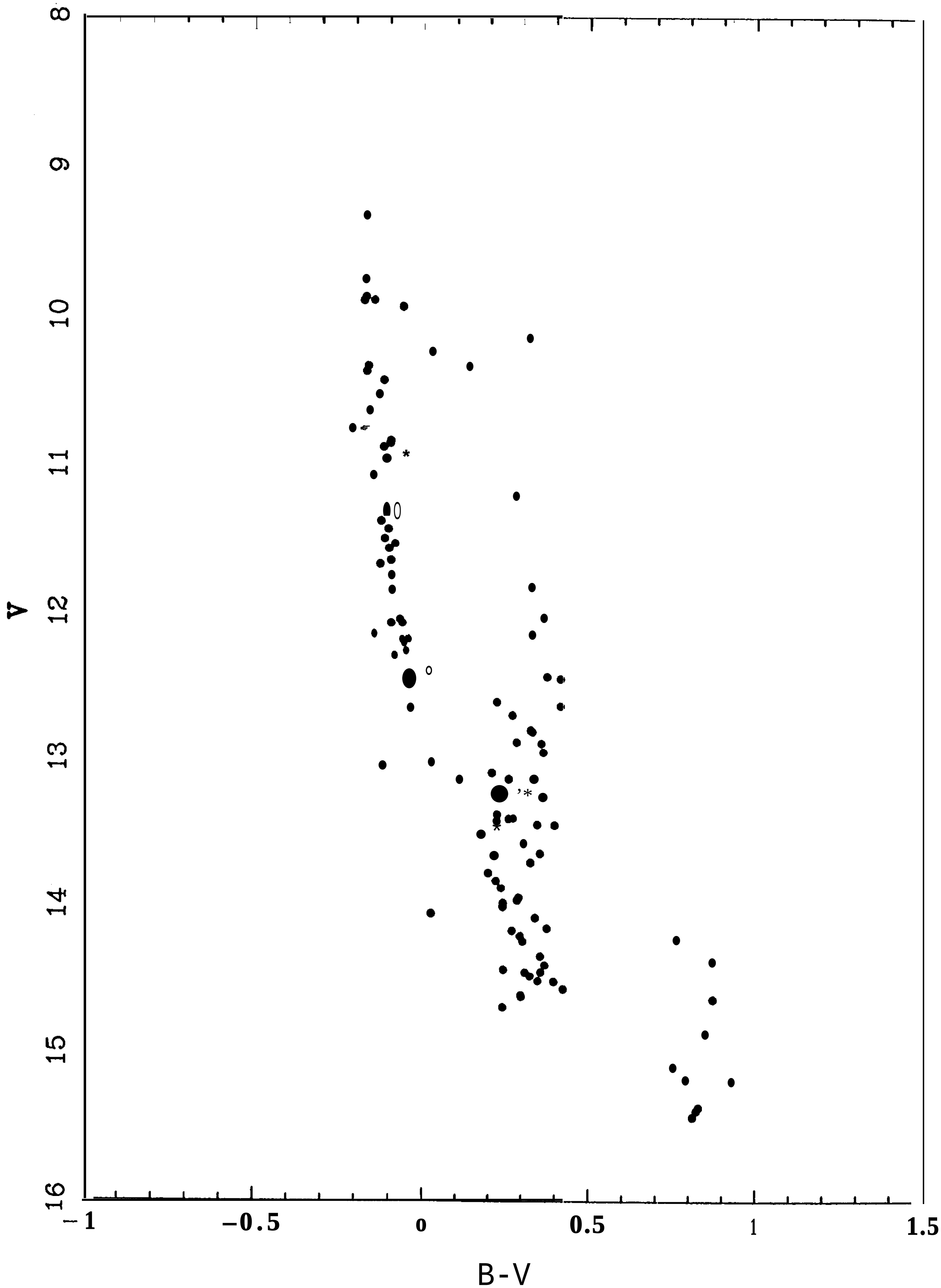


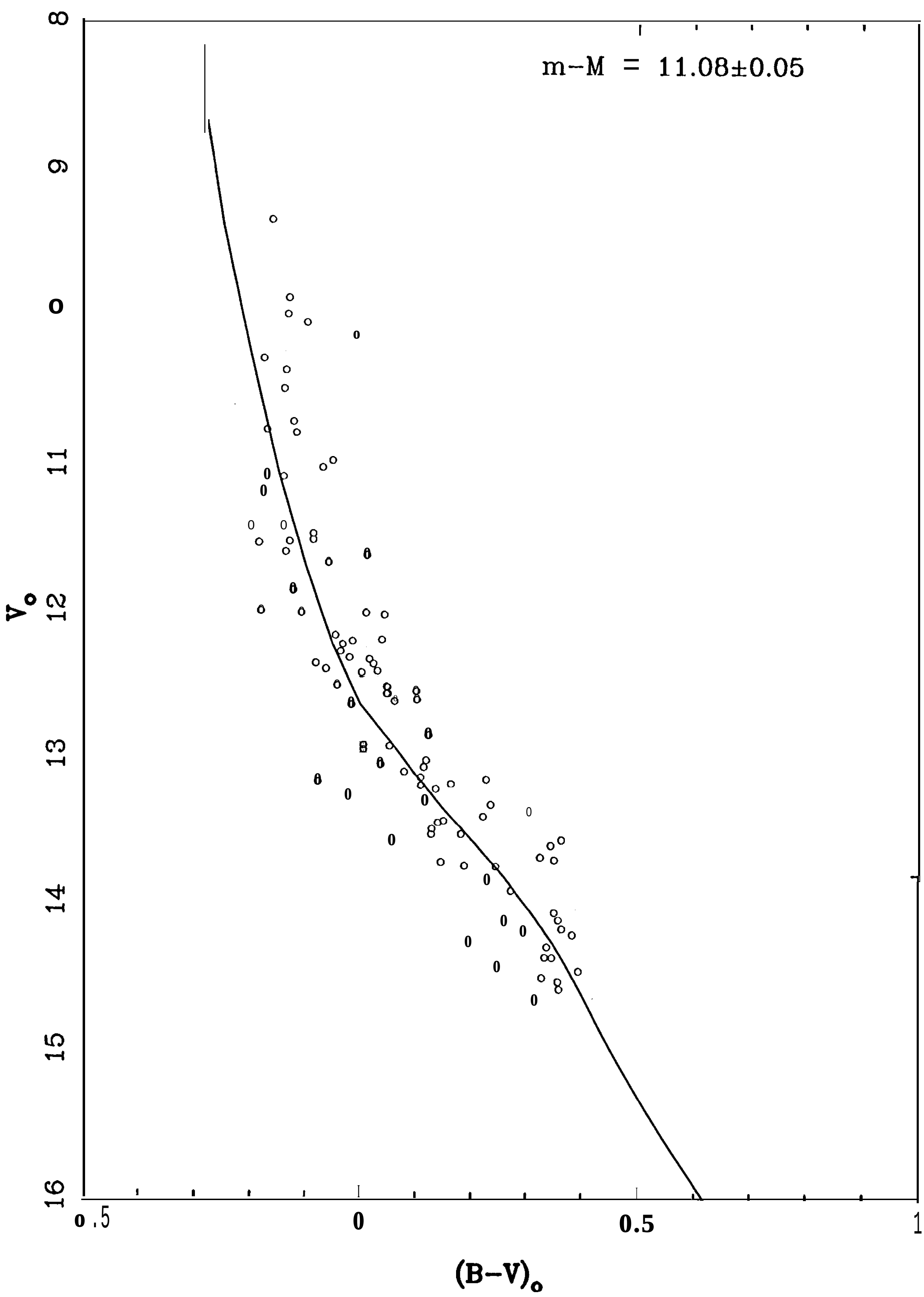
Δ(U−B) = −0.02 ±0.009
Δ(U−B)(H−T)
(U−B)T
0.2
0.1
0
−0.1
−0.2
−1
−0.5
0
0.5
1
1.5
2

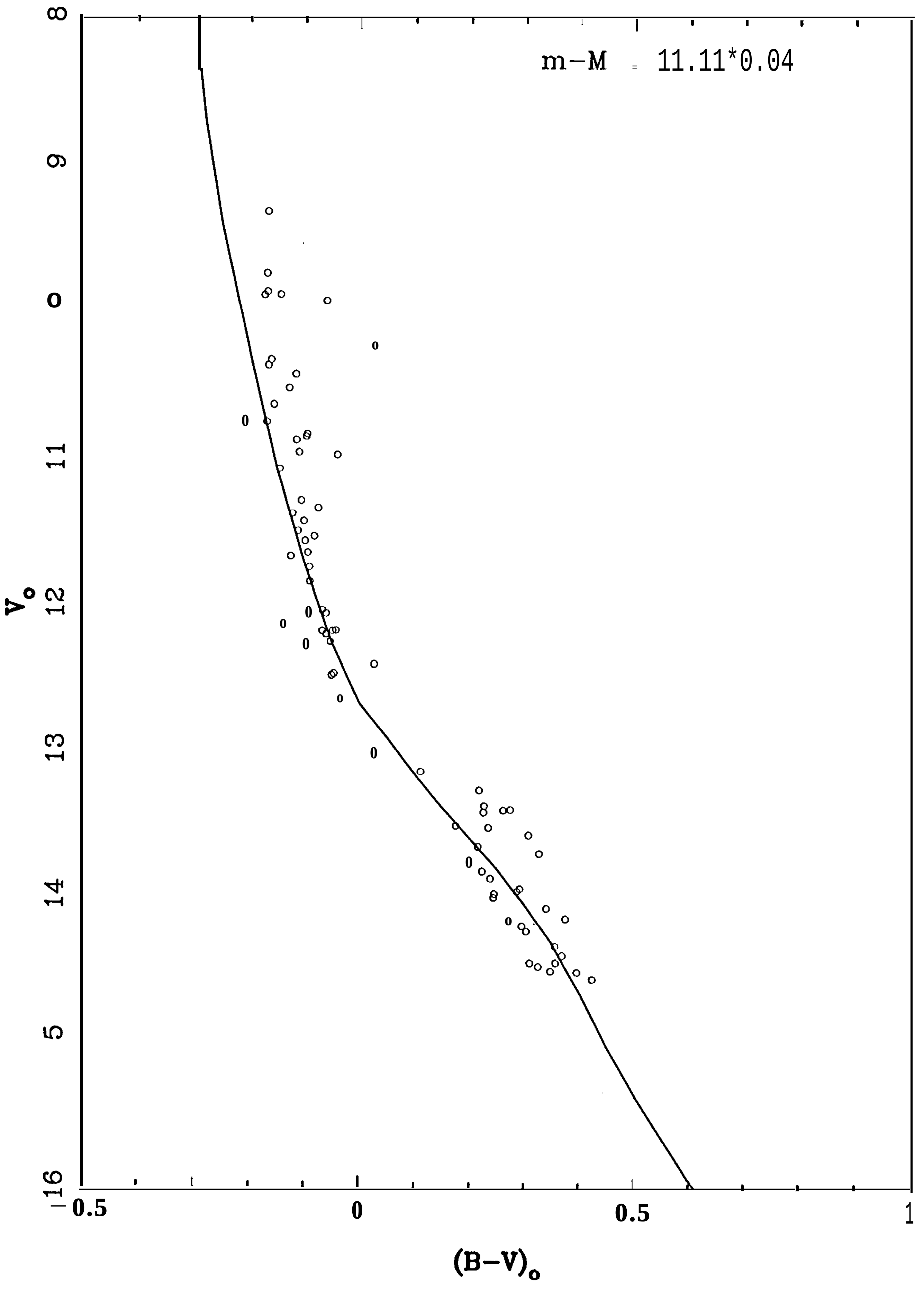

U-B
1
0.5
0
-0.5
-1
B-V
-0.5
0
0.5
1
1.5


U-B
1
0.5
0
-0.5
-1
B-V
-0.5
0
0.5
1
1.5

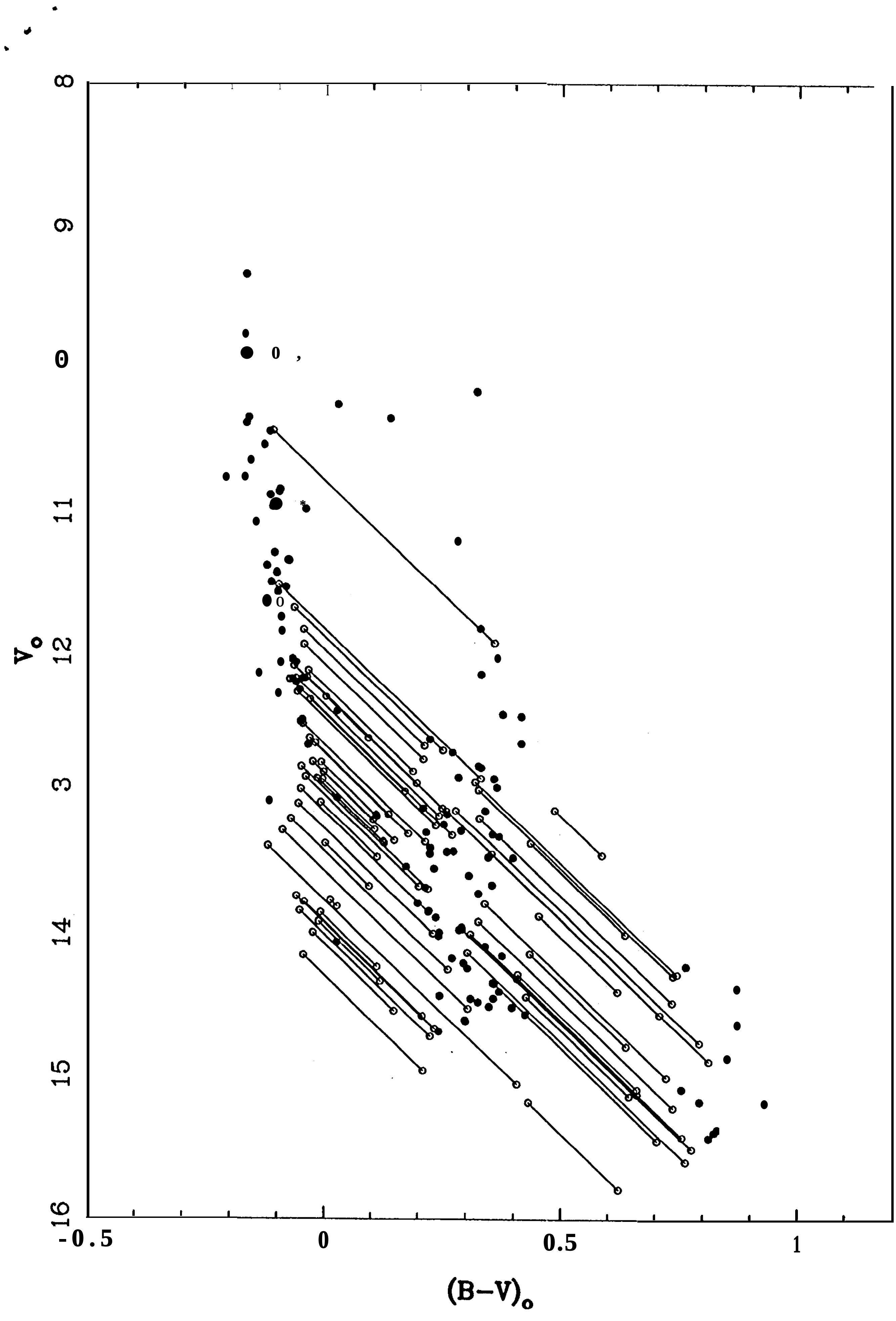

V
B-V
8
9
0
11
2
3
14
5
6
−1
−0.5
0
0.5
1


V
8
9
10
11
12
13
14
15
16
-1
-0.5
0
0.5
1
1.5
B-V

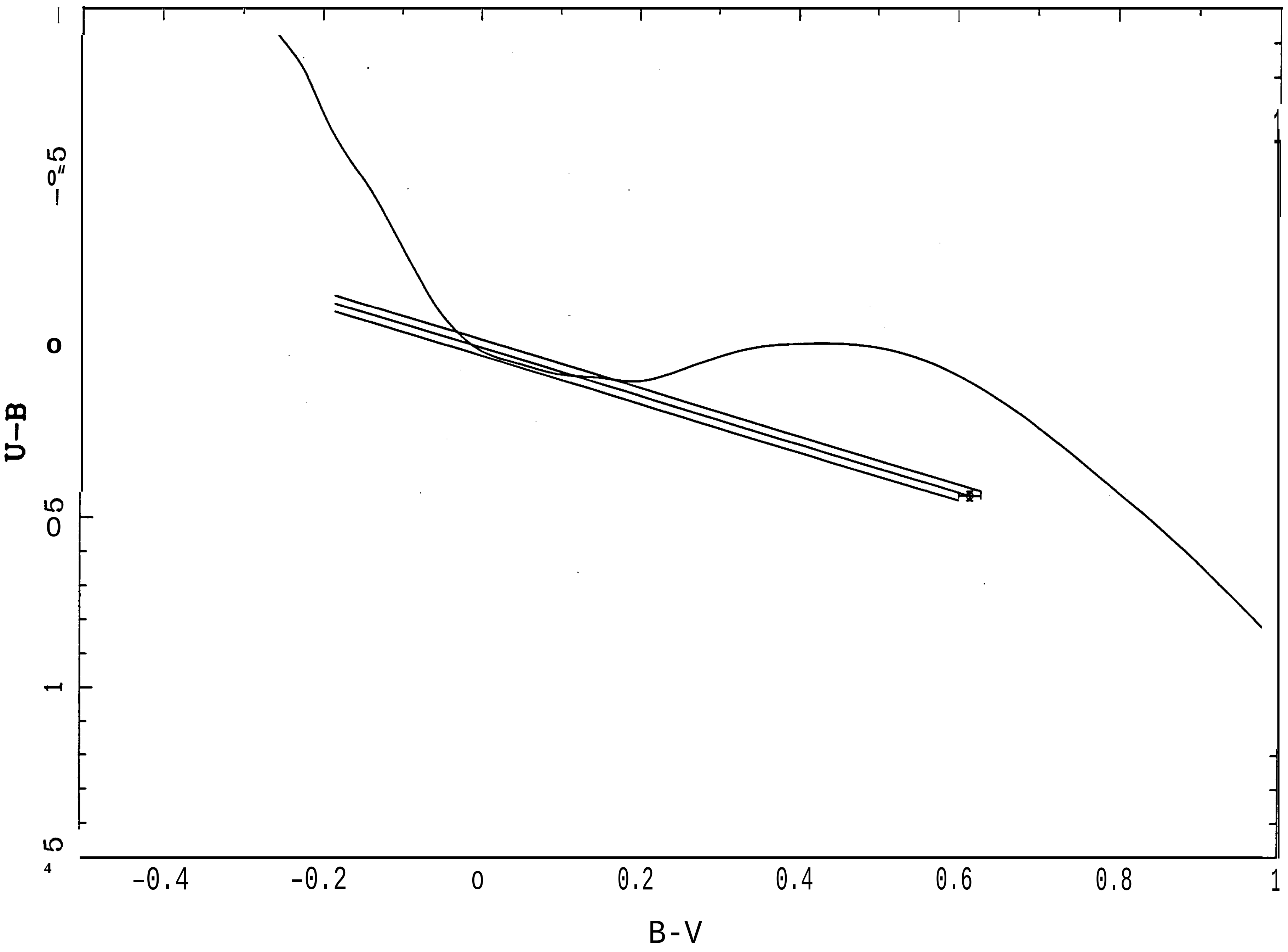

m−M = 11.08±0.05
V₀
8
9
0
11
12
13
14
15
16
0.5
0
0.5
1
(B−V)₀



m−M = 11.11*0.04
V$_o$
8
9
o
11
12
13
14
5
16
−0.5
0
0.5
1
(B−V)$_o$



8
9
0
11
V_o
12
3
14
15
16
-0.5
0
0.5
1
$(B-V)_o$



U-B
-0.5
0
0.5
1
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
B-V

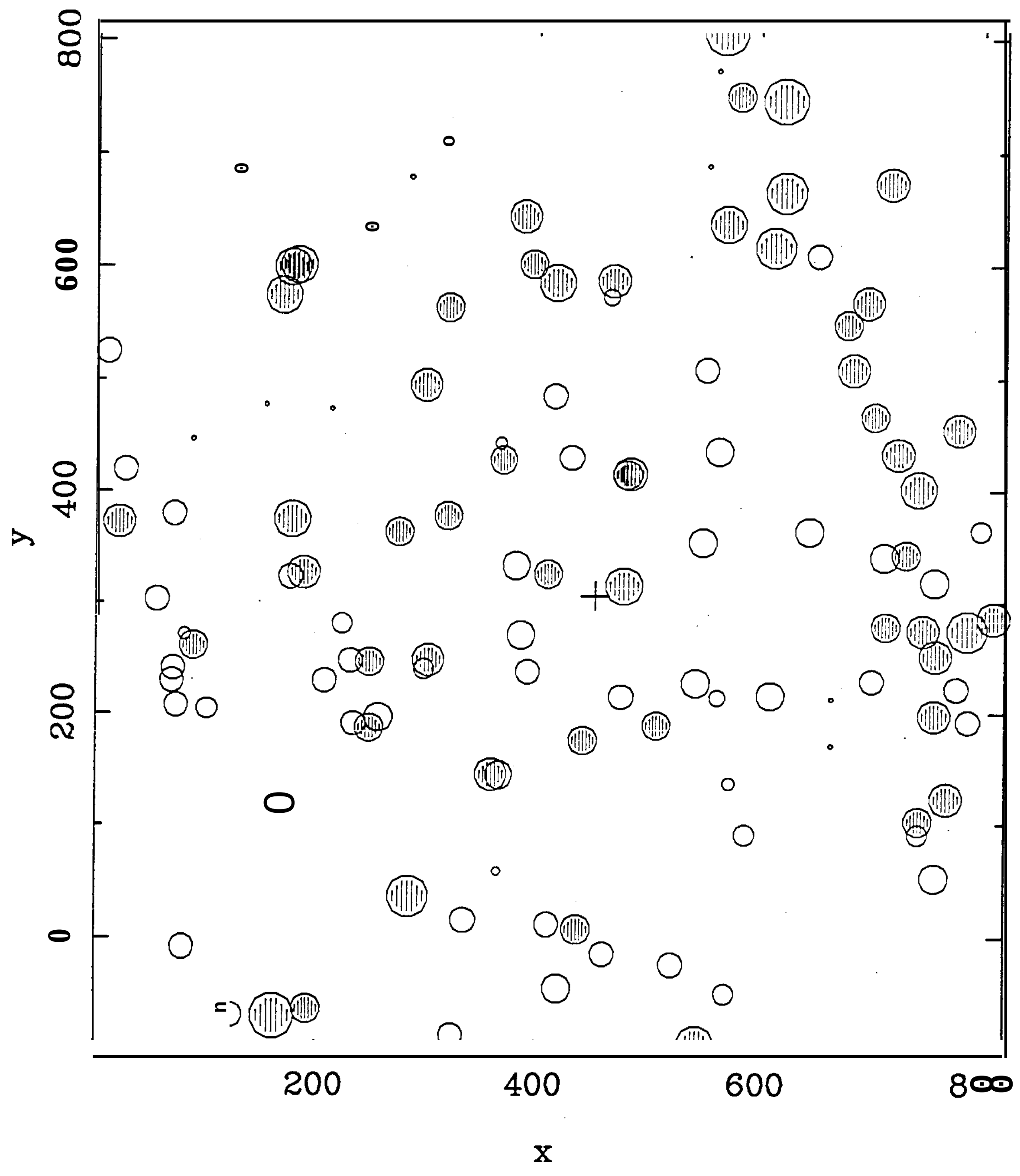


Table 1: Program Clusters

Cluster	Cepheid
NGC 129	DL Cas
NGC 7790	CEa Cas
	CEb Cas
	CF Cas
Anon	CV Mon
NGC 1647	SZ Tau
NGC 6(M9	V367 Set
NGC 6664	EV Sct
M 25	U Sgr

Table 2: Comparison of Photometric Zero-Points

Datasets	N_1	ΔV	$\Delta(B-V)$	N_2	$\Delta(U-B)$
Hill et al. - Turner et al.	17	-0.012 ± 0.009	$0.008 \pm$ 00006	15	-0.021 ± 0.009
Hill et al. - Hoag et al.	10	0.015 ± 0.006	0.017 ± 0.009	10	-0.016 ± 0.013
Hill et al. - Arp et al.	19	0.011 ± 0.007	0.046+ 0.012	16	$-0.040 \pm$ 0,031

Table 3: Photometry Of Previously Observed Stars In NGC 129

Star	A	T	H	X	Y	V	B-V	U-B	V-R	R-I
538	C	172	11	714.0	512.4	10.88	0.48	...	...	...
658	D	173	14	247.1	634.7	11.13	0.31	0.13	...	...
534	E	174	23	551.8	508.5	12.59	0.45	0.09	0,29	0.31
457	F	175		724.1	433.1	12.78	0.51	0.15	0.33	0.36
363	G	176		366.5	343.8	12.83	0.64	0.20	0.40	0.40
756	H	177		567.5	807,0	12.84	0.61	-0.01	...	...
460	I	178	25	563.7	435.6	12.89	0.42	-0.08	0.29	0.30
737	J	179	27	621.2	746.4	13.09	0.61	0.02	...	
437	L	181		295.0	410.9	13.93	1.59	1.30	...	...
281	M	182		386.0	271.1	14.23	0.60	0.44	0.36	0.37
535	O	184	30	683.7	508.5	14.14	0.55	0.27	0.34	0.37
242	P	185		589.9	237.6	14.42	0.67	0.43	0.41	0.41
636	R			652.1	609.3	14.64	0.91	0.38	. .	,..
587	T			319.2	563.7	15.03	0.70	0.50	. .	
738	U			581.4	750.3	14.95	0.79	0.50		...
466	V	191		299.0	442.9	15.00	0.68	0.48	...	...
292	W	192		590.2	278.6	15,26	0.71	0.45	0.44	0.41
528	X			351.4	501.5	15.28	0.99	0.47	0.62	0.65
714	Z			466.6	704.9	16.11	2.61	0.67	...	...
378	105	105	13	549.1	354.0	11.15	0.40	-0.16		...
455	121			431.2	430.0	12.17	0.43	0.01	...	...
342	125	125	18	410.7	325.6	11.79	0.43	-0.14	...	
598		115	15	466,1	572.8	11,44	0.73	0.30	...	...
678		96	20	622.5	665.7	12.24	0.56	-0,06	...	...
441		113	29	481.2	414.7	14.04	0.53	0.31	...	...

Table **4: Color Excesses For** Stars In The **Field Of NGC 129**

Star	z	Y	V	B-V	U-B	E(B-V)	Star	x	Y	V	B-V	U-B	E(B-V)
4	437.3	7.4	16.38	0.93	0.43	0.60	401	21.1	372.2	13.18	0.90	0.48	0.62
10	411.1	11.8	11.93	0.56	0.41	0.53	402	177.6	374.3	14.73	0.62	0.40	0.65
17	334.4	15.7	12.57	0.39	0.01	0.50	407	319.0	377.7	14.50	0.82	0.50	0.59
42	283.9	36.6	12,60	0.85	0.58	0.71	408	71.1	379.2	15.03	0.91	0.37	0.54
55	757,9	52.7	15.41	0.91	0.39	0,56	428	742.4	401.7	13.42	0.58	0.27	0.65
61	363.6	59.1	14.01	0.70	0.23	0.33	441	481.2	414.7	14.04	0.53	0.31	0.58
90	587.8	90.9	13.66	0.81	0.34	0.47	442	483.7	415.5	15.98	0.93	0.48	0,64
91	742.8	91.0	15.88	0.84	0.34	0,49	445	26.5	419.5	16.26	0.96	0.36	0.54
97	743,1	02.8	14.32	0.52	0,30	0.57	453	368.7	428.0	15.34	0.75	0.50	0.57
113	165.1	17.8	13.00	0.39	-0.04	0.51	455	431.2	430.0	12.17	0.43	0.01	0.55
117	768.0	22.5	15.52	0.92	0.45	0.61	457	724.1	433.1	12.78	0.51	0.15	0.61
131	573.7	36.4	13.19	0.73	0.25	0.37	460	563.7	435.6	12.89	0.42	-0.08	0.57
137	365.6	44.2	13.32	0.48	0.17	0,56	468	366.1	443.1	16.38	1.17	0.67	0.38
139	358.3	44.9	16.17	0.91	0.45	0.61	473	88.0	446.8	13.49	0.68	0.18	0.27
163	665.1	70.4	15.06	1.09	0.72	0.22	481	778.2	455.1	13.47	0,51	0.09	0.62
167	442.4	75.4	16.31	0.89	0.43	0.58	496	703.3	466.7	15.56	0.81	0.51	0.60
180	248.1	86.9	14.61	0.87	0.47	0.60	502	212.7	474.3	16.22	1.10	0.67	0,27
182	508.0	88,8	16.47	0.88	0,44	0.58	505	153.1	477.9	15.90	1.16	0.86	0.23
183	234.0	90.7	14.17	0.48	0,28	0.53	511	416.1	485.2	13.33	0.44	0.09	0.53
185	787.4	92.1	15,87	0.92	0.37	0.54	520	298,1	495.0	16.02	0.95	0.43	0.61
191	256.5	96.4	15.72	0.84	0.43	0.55	534	551.8	508.5	12.59	0.45	0.09	0.55
194	757.2	97.6	11.68	0.43	-0.14	0.60	535	683.7	508.5	14.14	0.55	0.27	0,61
19'9	101.3	04.6	12.51	0.44	0.26	0.48	547	10.1	524.7	14.98	0.73	0.44	0.50
204	73,3	07.6	13.23	0.42	0.07	0.52	587	319.2	563.7	15.03	0.70	0.50	0.59
206	665.4	13.2	15.81	1.15	0.74	0.30	591	696.8	567.7	14.24	0.57	0.33	0.62
209	562.8	14.3	14.44	0.76	0.29	0,42	598	466.1	572.8	11.44	0.73	0.30	0.41
212	476.5	15.1	16,24	0.81	0.39	0,51	601	168.6	574.6	15.27	0.93	0.53	0.67
214	610.9	16.1	13.97	0.52	0.31	0.56	607	417.1	585.6	15.60	0.95	0.54	0.69
222	776.9	22.2	13.82	0.46	0.13	0.55	611	468.1	587.4	14.01	0.55	0.29	0.61
227	543.0	27.7	15.50	0.89	0.41	0.56	622	176.3	599.3	15.63	0.97	0.54	0.70
229	701.7	29.2	13,40	0.43	0.10	0.52	627	181.9	601.4	15.97	0.90	0.54	0.66
230	207.6	29.8	12.09	0.39	-0.15	0.55	628	395.7	602.1	15.14	0.80	0.50	0.58
231	69.4	30.0	16.10	0.90	0.37	0,53	636	652.1	609.3	14.64	0.91	0.38	0.55
243	392.3	38.0	13.66	0.44	0.20	0.51	642	613.0	616.8	13.11	0.57	-0.04	0.74
247	297.3	40.4	13.37	0.82	0.35	0.49	658	247.1	634.7	11.13	0.31	0.13	0.38
248	70.5	41.2	16.33	0.76	0.44	0.52	659	570.2	637.8	15.61	0.89	0.54	0.65
253	248.6	46.8	13.28	0.48	0.10	0.58	665	387.8	644.6	15,18	0.87	0.50	0.62
254	231.3	47.9	12.89	0.39	0.02	0.50	678	622.5	665.7	12.24	0.56	-0.06	0.74
256	301.4	48.6	14.98	0.49	0.05	0.61	684	717.3	673.2	16.04	0.88	0.52	0.64
261	758.2	51.8	11.84	0.47	-0.05	0.61	690	283.5	679.8	15.51	1.15	0.77	0.28
270	89.1	61.5	14.21	0,50	0.13	0.60	699	127.4	685.5	16.22	1.11	0.58	0.36
281	386.0	71.1	14,23	0.60	0.44	0.57	700	553.1	689.2	16.29	1.11	0.67	0,28
282	80.8	71.8	13,61	0.78	0.24	0.36	717	317.2	710.1	15.47	1.16	0.62	0.39
286	786.5	74.6	16,23	0.95	0.57	0.70	737	621.2	746.4	13,09	0.61	0.02	0.77
288	746.9	74.9	16.49	1.02	0.43	0.62	738	581.4	750.3	14.95	0.79	0.50	0.58
291	713,9	78.6	16.33	0.92	0.40	0.57	750	561.5	772.9	16.25	1.07	0.63	0.26
294	223.5	81.2	13.23	0.36	-0.05	0.49	756	567.5	807,0	12.84	0.61	-0.01	0.77
315	55.6	03.0	16.07	0.76	0.43	0.51	769	544,7	-95.1	15.39	0.96	0.50	0.67
330	478.6	14.8	15,12	0.68	0.51	0.65	776	323.9	-87.1	13.81	0.38	-0.10	0.52
333	757.2	17.9	16.00	0.86	0.43	0.56	786	161.6	-69.8	13.18	0.55	-0.20	0.76
339	176.6	23.1	15.09	0.91	0.35	0.51	788	123.0	-68.9	14.56	0,88	0.39	0.55
342	410.7	25.6	11.79	0.43	-0.14	0.60	792	192.3	-63.3	15.18	0.95	0.41	0.60
344	188.4	26.7	12.83	0.50	0.06	0.61	804	570.4	-50.0	13.34	0.38	0.08	0.47
349	381.1	33.3	15.54	0.75	0.49	0.55	810	420.4	-45.0	15.93	0.83	0.44	0.55
356	712.3	40.5	12.29	0.43	-0.03	0.55	828	522.3	-24.0	16.17	0.90	0.38	0.54
361	731,5	42.8	14.09	0.53	0.28	0.59	834	461.2	-14.3	15.75	0.56	0.41	0.53
378	549,1	54.0	11.15	0.40	-0.16	0.57	839	79.7	-8.1	14.19	0.93	0.38	0.55
392	274.7	63.4	14.63	0.90	0.41	0.57	946	809.8	285.8	15.51	0.99	0.45	0.65
394	644.8	63.5	15.22	0.79	0.48	0.56	1270	678.7	548.4	15.65	0.79	0.49	0.57
395	798.2	64.2	14.43	0.77	0.38	0.49							